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Virtual Ipoh International Summit on Professionalisme, Research and Education 2022

IeGRESAFE 2022

E-PROCEEDING OF

1st INTERNATIONAL E-CONFERENCE ON GREEN & SAFE CITIES 2022

"Sustaining the Resilient, Beautiful and Safe Cities for a Better Quality of Life"

20 & 21 SEPTEMBER 2022

Organisers:

GRESAFE_CITIES
Green Safe Cities, Research Interest Group

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

UITM CAWANGAN PERAK KAMPUS HIJAU

Co-organisers:

OFFICE OF RESEARCH, INDUSTRIAL LINKAGES, COMMUNITY & ALUMNI (PJIM&A), SERI ISKANDAR CAMPUS
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ORGANISED BY

Gresafe_Cities RIG
The University of Queensland, Australia
Kampus Hijau UiTM Perak

CO-ORGANISED BY

Research, Industrial Linkages, Community & Alumni Network (PJIM&A)

Perpustakaan Negara Malaysia Cataloguing in Publication Data

No e ISBN: 978-967-2776-13-0

Cover Design: Muhammad Falihin Jasmi

Typesetting : Ts Dr Azizah Md Ajis

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REVIEW OF IMPACTS OF BIOMIMETIC MANGROVE STRUCTURES ON WAVE ATTENUATION AS REGENERATIVE BUILDING STRATEGY

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Abstract

The increase in human population leads to the exploration and migration to urban and coastal zones, encouraging the changes in mitigating strategies for coastal protection, especially as the climate change effects exacerbate the natural environmental challenges. Currently, the mitigation strategies implemented lead to the introduction of hard and soft structures as coastal protection measures. However, integrating these hard structures has turned out to be ineffective in fully mitigating the coastal erosion issues leading to an unending chain problem. The introduction of mangroves as the soft structure remains challenging due to the time required for the establishment and uncertainties in functionality and persistence of mangroves which depends on a range of environmental conditions. Biomimicry encompasses bio-inspired approaches in developing design solutions in a sustainable paradigm while focusing on benefitting local ecology, harvesting the benefits of ecosystem services, and accommodating adaptation through regenerative ecosystems. With reference to this strategy, the study concentrates on mangroves as the basis for proposing a regenerative design solution, focusing on their dynamic and resilience properties. The proposed key element in wave attenuation and mitigating erosion is the study of hydrodynamic interaction between mangrove roots and water flow, focusing on the interactions between root porosity, water flows, and sediment transportation. Based on the literature review, the potential research gap identified is the integration of wave attenuation properties of mangrove roots into the structural design, which contributes to a regenerative building strategy, benefitting both the built environment and ecosystems.

Keywords: *Biomimicry, Mangrove Structure, Wave Attenuation, Architectural Adaptation, Regenerative Building Design.*

INTRODUCTION

The human population has been increasing exponentially over the years, along with the need for food, water, air, and shelter to survive. According to Stachew et al. (2021), the exponential increase in the human population leads to the exploration and relocation to urban and coastal areas, which eventually lead to the building over natural ecosystems. The climate change effects intensify the impacts caused by these changes, leading to a shift in the built environment paradigm to co-exist with nature.

The understanding of morphologic processes in the mangrove forests due to waves and tidal currents is fundamental for the preservation of these mangrove coasts as well as the communities and infrastructures behind the embankments. Along with other significance of mangrove forests to the mitigation of climate change, Sidik et al. (2018) and Alongi (2020) highlighted the importance of mangrove forests as the largest carbon sink compared to other ecosystems and the loss of mangroves, in turn, leads to a significant release of stored carbon. In addition, a study by Sandilyan & Kathiresan (2015) shows that mangroves play important roles in coastal protection against natural occasions such as cyclones, typhoons, as well as tidal waves in several parts of the tropical region. The preservation of the mangroves allows the continuous benefit of coastal protection in addition to the services provided by them.

Existing artificial barriers, while being expensive to build and maintain, are influencing sediment transport, thus reducing the ability of the shoreline to respond to environmental challenges. As coastal barriers greatly impacted the configuration of the shoreline, a study by Ariffin et al. (2018) shows that the extension structure imposed on the coast of Kuala Terengganu, Malaysia causes the alteration of the hydrodynamics circulation and sediment transport, which leads to the inhibition of the natural response of coast to monsoonal storms and erosion. Curved sea walls, for instance, reflect the wave energy to the sea, causing the waves to remain powerful. On the other hand, the construction and placement of groynes, artificial structures, and detached breakwaters, although able to protect the eroded shore, have obstructed longshore sediment transport, thus causing disruption in the natural hydrodynamic processes and coastline progression (Mohamed Rashidi et al., 2021). The issues with the artificial barriers are encouraging researchers to shift their focus of study by referring to the natural defence mechanism in terms of coastal and infrastructure protection against the impacts of intensifying natural occurrences.

Therefore, the study aims to provide an extensive review of the mangrove forest ecosystem as the proposed design alternatives inspired by the nature in terms of the natural defence mechanism from the environmental challenges to better identify the potential and applicability of the implementation. This review paper uses qualitative research to discuss the theoretical approach to embedded architecture, which involves employing biomimicry. Thence, this paper further summarises the existing literature on the application of the approach relating to the mangrove ecosystem as a potential of extracting mangroves' qualities for the climate change mitigation strategy on the coastline and riverine issues in Malaysia. In addition, a general overview of the wave attenuation properties of the mangroves and the implementation is provided to understand the practicality of the application based on the analysis of the hydrodynamic interaction between mangrove roots and water flow.

It could be observed that many studies have been conducted to understand the hydrodynamic interactions between the roots and the water flow of mangroves (Kazemi et al., 2021; Abdillah et al., 2014; Zhang et al., 2015). However, further knowledge of fluid dynamics is required to better understand the complexity of each study. Thus, this review analyses the existing literature based on the general aspect of the application, without advancing the discussion into the scientific knowledge of fluid dynamics.

LITERATURE STUDIES

Biomimicry in Architecture

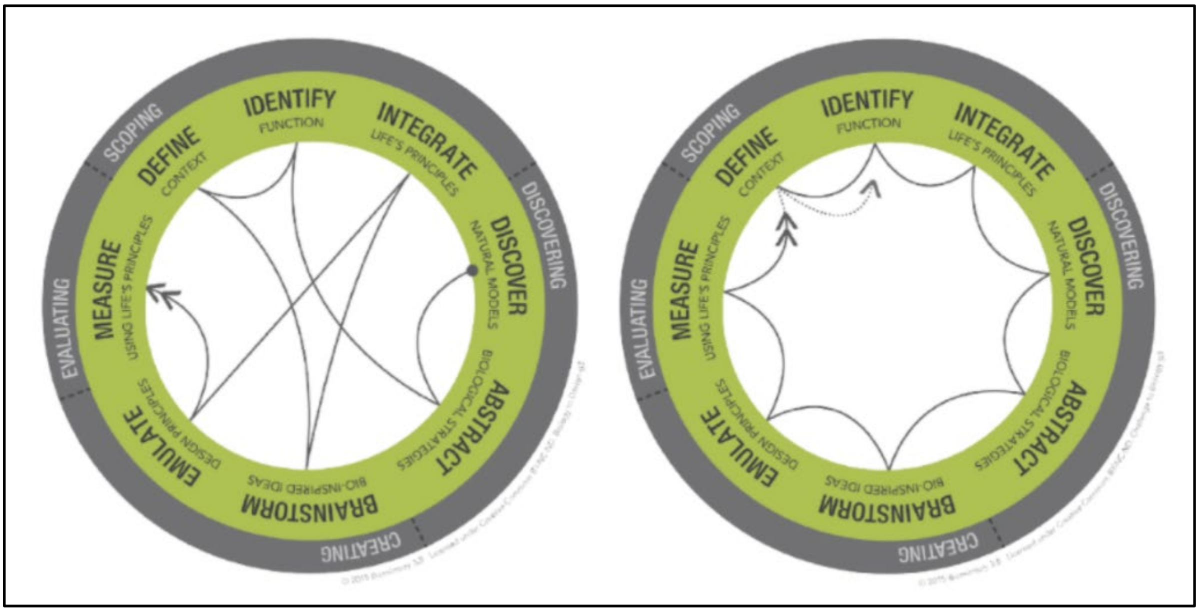
Biomimicry in architecture encompasses bio-inspired approaches in developing design solutions in terms of forms, techniques, and functions and is explored to shift the built environment to a more sustainable paradigm. Biomimicry exhibits a potential role in addressing climate change, either by mitigating the causes or adapting to the impacts. The integration of a thorough understanding of natural systems into architectural design posited an opportunity for building adaptation to climate change issues (Zari, 2010). Concerns on intensifying environmental challenges, including climate change and global warming, have driven proliferated studies on regenerative building design. As nature models the evolution and adaptation to environmental challenges, it is logical to study and emulate nature to further achieve optimisation in terms of sustainability and efficiency in design and construction. Deriving design solutions from nature has offered an opportunity to maximise resource efficiency while mitigating the negative impacts of buildings on the environment (Nkandu & Alibaba, 2018).

The implementation of biomimicry in design involves the abstraction of beneficial qualities from nature and adapting into an optimised morphological or functional context to realise the design objectives (Amer, 2018). According to Nkandu & Alibaba (2018), generally, there are two main approaches in the application of biomimicry in the design process: problem-based approach and solution-based approach. Both approaches are observed to have different terminologies in various studies. For instance, the problem-based approach is also referred to as *top-down* (Syed, 2021), *design looking to biology* (Abdel Rahman, 2021), and *problem-driven approach* (Gamage & Hyde, 2012), while the solution-based approach is known as *bottom-up* (Syed, 2021), *biology influencing design* (Abdel Rahman, 2021) and *solution-driven approach* (Gamage & Hyde, 2012).

As described by Badarnah & Kadri (2015), the main concept of the problem-based approach is identifying the design problems in relation to adaptation requirements and looking for solutions in nature. This approach depends on the identification of the design's objectives and limitations and essentially suggests that there is potential in creating a systematic search process in order to address the adaptation requirement of the design problem (Radwan & Osama, 2016; Badarnah & Kadri, 2015). For example, Muntinga (2010) compared and assessed the pinnacles of several natural characteristics before choosing the best pinnacle to be developed into the façade design.

On the other hand, the solution-based approach is where the inspiration from nature is translated into the design. The design process under this approach involves depending on the scientific knowledge of nature and extraction to be utilised as the design principles and strategies (Radwan & Osama, 2016). Thus, the solution-based approach is observed not to address the application of a scientific systematic method for bio-inspired technological design as the solutions derived from the specific knowledge of biology may not necessarily be predetermined (Imani et al., 2017). For instance, Fecheyr-Lippens & Bhiwapurkar (2017) applied the solution-based biomimicry methodology adapted from Badarnah & Kadri (2015) by studying the African reed frog and Hercules beetles in order not to restrict their design process to a specific problem.

Figure 1
The two approaches of biomimetic design to architecture as developed by Biomimicry Institute adapted from Brodrick (2020): problem-based approach (left) and solution-based approach (right).



Coastline and riverine issues in Malaysia

Malaysia consists of approximately 4,810 km of coastline, which is spread along the West Coast Peninsular (1110km), East Coast Peninsular (860km), Sabah (1743 km), and Sarawak (1035 km) (Abd Shukor, 2004). According to Integrated Coastal Management (2005), the coastal zone of Malaysia is commonly densely populated and has become the targeted site for urbanisation (Sahabat Alam Malaysia, 2020). Due to current environmental challenges, the coastline of Malaysia is exposed to the pressure of rising sea levels and coastal degradation. National Coastal Erosion Study 2015 outlined that 15% of 8840 km of coastline are presently degrading and one-third of those critically require further protection (Mohamed Rashidi et al., 2021). The impacts of anthropogenic activities, for instance, the coastal reclamation, combined with natural forces on the coastal erosion, are exacerbated by climate change. Without proper adaptation measures, sea level rise of one meter is expected to cause 180,000 ha of agricultural land loss and 15%-20% of coastline mangrove forest loss while subsequently threatening coastal population and development (Ehsan et al., 2018). In addition, both sea level rise and projected hurricane intensifications lead to surge amplifications which intensify the adverse impacts of coastal flooding and storm surges that subsequently pose risks to the communities and infrastructures along the shoreline (Cheikh & Momen, 2020). According to Nadal et al. (2020), floods in the riverine and coastal areas cause significant damage to infrastructures along the shoreline, including the failures of the structural system of the buildings.

Referring to Mohamed Rashidi et al. (2021), the coastal processes in Malaysia are heavily affected by the East Asian monsoon system which brings a great intensity of physical occurrences related to waves, current velocities, winds, and high rainfall frequency. This subsequently affects the dynamic processes of coastal zones, including coastal erosion and accretion. The reclamation projects for development, including the 1,765 ha of land before 2008 in Penang, 8,094 ha of land in 1997 in Setiawan, Perak, and 1,504.9 ha in Melaka Gateway, intensify the impacts as they are often associated with the loss of coastal ecosystems, including mangroves, mudflats, and seagrass, which act as natural buffers against the physical phenomena (Sahabat Alam Malaysia, 2020).

Among the mitigation strategies implemented is the introduction of hard and soft structures as coastal protection measures. The hard coastal protection structures, including the groyne, breakwater, and revetment, are implemented along the shoreline to reconstruct the coastal dynamics. A groyne, for example, is built from the coastal shore or riverbank for the purpose of interrupting the water flow and limiting the sediment movement (Zulfakar et al., 2020). The study further demonstrated that the implementation of these structures as coastal protection measures along the shoreline of Kuala Nerus has slowed down the erosion rate, promoted the occurrence of accretion, and reduced the intensity of the incoming current. Nevertheless, the integration of these structures has turned out to be ineffective in fully mitigating the coastal erosion issues as the erosion has been shifted to the upper part of the Kuala Nerus shore, possibly due to the recirculation current, leading to an unending chain problem (Figure 2).

Figure 2

The jetty groyne of Tok Jembal faced shore erosion despite having revetment protection.

Adapted from Zulfakar et al. (2020).

Several other studies have also manifested the negative impacts of the coastal protection structures (Mohamed Rashidi et al., 2021; Moosavi, 2017; Gracia et al., 2018). Additionally, Noble (1978) found that the consequent erosion and sediment deposition from implementing these structures lead to additional costs and continuous maintenance operations.

Besides, coastal protection can also be achieved using the soft structure (mangrove and coral reefs). For instance, due to the ecosystem services that can be provided by mangrove forests including the ability to increase accretion while reducing erosion, the Malaysian government has also begun to invest in mangrove restoration and conservation as long-term, sustainable, and cost-effective coastal protection initiatives (Hashim et al., 2010; Hashim & Shahruzzaman, 2017). The presence of vegetation contributes to wave dissipation and structural fragility reduction as opposed to the bare-earth area (Kyprioti et al., 2021). According to Sabari et al. (2021), the World Conservation Union recorded about 6000 deaths in locations without vegetation during the Indian Ocean Tsunami in 2004, instead of only two deaths in the densely vegetated area. The mangroves, however, are unable to mitigate the significant destruction in the highest tsunami density locations.

However, these efforts remain challenging due to the time required for the establishment as well as uncertainties in functionality and persistence of mangroves which depends on a range of environmental conditions (Gijsman et al., 2021). Furthermore, this direct planting method is not often successful without the removal of stressors and the provision of suitable environments to facilitate the re-establishment (Kamali & Hashim, 2011). Therefore, the integration of mangrove potentials into the built environment would provide an opportunity for betterment in both architectural and ecological aspects.

Mangrove as an embedded architectural approach

Along with defensive and reactive strategies in climate change adaptations of buildings, embedded architecture, which involves employing biomimicry, focuses on benefitting local ecology, harvesting the benefits of ecosystem services, and accommodating adaptation in depth through regenerative ecosystems (Poulsen et al., 2019). This strategy contributes to the development of sustainable adaptation of buildings to respond to the changes, in this case, the sea level rise. The shift from 'coastal armouring' and hard-engineered defence structures to this ecologically informed approach creates an opportunity to design structures that are able to perform beyond engineering means while providing ecological and social benefits (Moosavi, 2017).

With reference to this strategy, the study concentrates on mangroves as the basis for proposing a regenerative design solution, focusing on their dynamic and resilience properties. Mangrove forest, characterised by tropical trees and shrubs which can be found along coastlines, mudflats, and riverbanks, is recognised as one of the most dynamic and biologically important ecosystems due to the intangible and tangible goods and services provided (Wang et al., 2019). These include building and binding soils, climate change resilience, increasing biodiversity, improving water quality, providing raw materials, recreation services, and acting as carbon dioxide sinks (Maza et al., 2019).

The various ecological services provided by the mangroves lead to the bio-inspired integration into man-made features, morphologically and functionally, as shown in Table 1.

Table 1

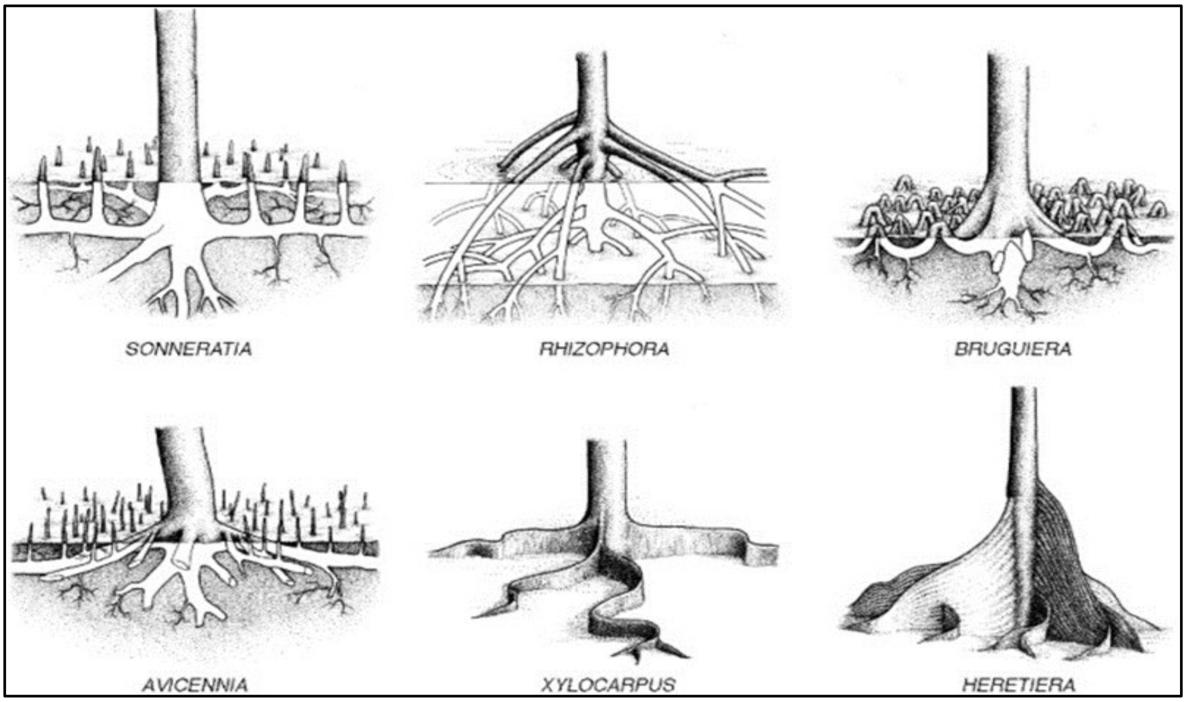
Integration of mangroves in biomimetic approaches

	Author/year	Location	Methodology	Findings
1	Rao (2014)	India	Literature Review	The proposal of the futuristic skyscraper 'Mangal City' in London by Chimera takes inspiration from the nature of mangrove trees and spiralling plant growth patterns. The adaptive urban ecological system responds to environmental and contextual conditions.
2	Cui et al. (2019)	China & Hong Kong	Laboratory experiment	The authors proposed a bio-inspired design of an anti-corrosion coating based on the mangrove leaves that have salt glands that are able to secrete excessive ions, helping mangroves to thrive in tidal zones with high salinity and humidity. The coatings are found to effectively block and control the transport of both Na^+ and Cl^- and together with the hydrophobic surface, the coating systems manifested greater anti-

				corrosion properties as compared to the control group (epoxy finish).
3	Abd El-Rahman et al. (2020)	Cairo, Egypt	Computational and building simulation tools	The authors proposed a conceptual biomimetic model of adaptive building façade with a dynamic shading system based on mangrove flower, cactus form, and the Giant White Ipomoea (Morning Glory) for buildings in hot climate (Cairo). Based on the simulation study, the proposed system contributes to glare reduction, daylight penetration improvement, and over 50% reduction in solar gain.

A potential attribute of their resilience property lies in their complex root systems, which can be highly effective to attenuate wave energy (Kazemi et al., 2018). In general, the root systems of mangrove species include surface roots, stilt roots, pneumatophores, and aerial roots (Figure 3). Referring to Goltenboth & Schoppe (2006), Avicennia sp. and Sonneratia sp. are characterised by radiating cable roots from the radial roots with vertical pneumatophores protruding above the surface. Meanwhile, Rhizophora sp. has prop roots that break into air-filled anchoring roots and downward-growing stilts roots for a further anchor in the mud. Brugeira sp. has knee-like loop roots that function as pneumatophores with lenticels, while Xylocarpus sp. has horizontal roots that are compressed into narrow upward flanges (Goltenboth & Schoppe, 2006).

Figure 3
Rooting and aeration system of some mangrove species.



Adapted from Goltenboth & Schoppe (2006).

Wave attenuation

The basis of the strategies in mitigating the flood risk and other coastal challenges in protecting the shoreline ecosystem and development often follows these three principles: protection, wave attenuation and energy dissipation, and cohabitation (Moosavi, 2017). Cohabitation includes the regenerative building strategy, which involves the integration of structural and landscape-based approaches.

The study focuses on the mangrove ecosystem as it provides valuable natural coastal protection both directly and indirectly in the forms of dissipating storm surges and waves and retaining sediment accretion within their complex root system (Marois & Mitsch, 2014). According to McIvor et al. (2012), mangrove is capable of reducing wave energy and height over a relatively short distance as between 13% to 66% of wave height is reduced over 100 m mangroves. The main factor affecting wave attenuation in mangroves is the density of blockages encountered by the waves as they pass through the mangrove, as well as the height of the blockages in relation to the water depth (McIvor et al., 2012). The variation of mangrove structural parts between species, in terms of sizes and forms, leads to differences in their level of resistance to water flow while their complex root system provides greater drag force (Sabari, 2021). Table 2 summarises the contributions of mangrove plant characteristics and wave hydraulic features towards wave attenuation.

Table 2

Summary of the contributions of mangrove plants characteristics and wave hydraulic features towards wave attenuation.

	Feature	Contribution
1	Mangrove density	Denser forest attenuates waves more effectively
2	Forest structure and width	Narrow forest width can be adopted for coastal protection when vegetation is tall and thick
3	Water depth	Resistance to wave increases with water depth in vegetated areas due to submergence of the extra shoot but decreases with water depth for non-vegetated areas
4	Incident wave height	Wave attenuation varies linearly with incident wave height in mangrove-protected zones but is independent of the height for non-vegetated areas
5	*Rhizophora sp.* and *Bruguiera sp.* have complex and bigger aerial roots compared to *Kandelia candel*	*Rhizophora sp.* and *Bruguiera sp.* provide greater drag force and extra resistance to waves attack than *Kandelia candel*
6	Mangrove age	Mature trees are stiffer, more structurally stable, and less susceptible to uprooting/breakage, therefore better attenuation capacity
7	*Spartina anglica* has a stiffer shoot compared to *Zostera noltii sp*	*Spartina anglica* dissipates hydrodynamic forces up to about three times higher than *Zostera noltii*

Adapted from Sabari et al. (2021).

Mangrove root model

The proposed key element in wave attenuation and mitigating erosion is the study of hydrodynamic interaction between mangrove roots and water flow, focusing on the interactions between root porosity, water flows, as well as sediment transportation (Kazemi et al., 2021).

Stachew et al. (2021) proposed a framework for establishing a root-inspired structure with regard to adaptation and functionality. This includes the adaptation to varying external loads such as tidal height, storm surge, sediment movement and the addition of ecosystem services such as habitats provision as well as nutrient cycling. Furthermore, the study may cover the most practical scale for the functions of a) wave dissipation and dispersion, (b) flow speeds for sediment deposition, and (c) space for habitat provision. The hydrodynamic analysis may also focus on the vorticity (rotation) and turbulent kinetic energy as the flow structure parameters. The flow rotation determines if sediment will be carried or deposited downstream. On the other hand, turbulence is a crucial element in the indication of sediment motion initiation. Both influence the sediment build-up around the roots, which allows the trees to rise with the sea level.

The hydrodynamic analysis of the interaction of the complex mangrove roots system during tidal flow conditions can be studied using simplified models. The roots are modelled with a circular array of cylinders (patch) with different porosities and spacing ratios that are often used to model rigid emergent vegetation (Kazemi, 2017; Wang et al., 2022). According to Kazemi et al. (2017), porosity refers to the ratio of the volume occupied by the roots to the volume occupied by water for confined space below the surface of the water. The boundary layer behind the permeable patch demonstrates the impact of patch porosity on the beginning of sediment transport (Kazemi et al., 2021).

Table 3 shows several studies that include the hydrodynamic analysis between root-inspired models (nonexclusive to mangrove roots) and the focused key parameters to analyse the wave attenuation properties of the models.

Table 3
Compilation of studies of hydrodynamic analysis for root-inspired models.

	Author/year	Location	Methodology	Findings
1	Zhang et al. (2015)	Singapore	Physical experiment	The prop roots create a blockage to the flow and cause complex secondary flow. The force balance analysis to study the flow resistance shows that the Chézy roughness coefficient C was 10 and the drag coefficient CD was found to be 1.2 in the fully developed flow, which corresponds to the reported field studies in mangrove swamps.
2	Kazemi et al. (2017)	United States of America	Experiment using physical models in 2D soap-film flow visualisation.	The effective diameter of the patch decreases when the porosity between the members increases. Besides, the patch drag is directly proportional to patch diameter and indirectly proportional to the spacing ratio.
3	Bedi et al. (2020)	France	Physical simulation	The optimisation of solution efficiency in terms of maximising energy dissipation and minimising energy transmission of the developed mangrove-inspired ROOT model is affected by the porosity, roughness, tortuosity, and structure length. The wave flume simulation found that the

				model with varying porosities (τ=90% and 70%) has the maximum energy dissipation and minimum energy reflection, thus making it the best compromise for efficient wave attenuation.
4	Stachew et al. (2021)	Ohio, United States of America	Literature review and conceptual framework proposal	The principles of root biology are adapted into conceptual designs for foundation and coastal infrastructures that prevent soil erosion and anchor structures while providing natural habitat. Conceptually, complex morphologies, such as the root systems, could be adapted into multifunctional coastal structure design as they provide protection against wave action and stabilise the sedimentation process to provide anchorage for the aboveground structures.
5	Kazemi et al. (2021)	United States of America	Physical simulation	The patch with the ϕ=47% porosity is found to have the maximum critical velocity for the initiation of sediment transport. The sediment erosion for the patch with optimum porosity is minimal while creating negative vorticity near the bed, similar to mangrove porosity in nature.
6	Wang et al. (2022)	China	Physical experiment	The wave-attenuation analysis shows that the influence of the root model on wave attenuation reduces gradually as the water depth increases.

Based on Table 3, it could be observed that the integration of the mangrove roots as a simplified roots model enables further understanding of the hydrodynamic interaction between the model porosity and impact on the water flow. The findings of these studies are extracted and implemented in the design process as an embedded architectural approach which contributes to the mitigation of the climate change effects as mentioned previously. Zhang et al. (2015), Bedi et al. (2020), and Wang et al. (2022) demonstrate that the root models are able to attenuate the wave energy as the mangrove roots would in nature. On the other hand, not limited to the wave attenuation, Kazemi et al. (2017), Stachew et al. (2021), and Kazemi et al. (2021) further emulate the roots properties of mangroves in terms of the energy dissipation, sedimentation onset as well as sediment transportation into their root's models.

In addition, due to their unique resilience properties, it can be observed that several studies have shown interest in proposing and developing an eco-inspired solution for coastal dynamic problems including biomimetic porous breakwaters inspired by the mangrove roots system (Fatimah et al., 2008; Winterwerp at al., 2020). The evaluation of the performance of the proposed solutions also includes the sedimentation dynamics as this helps in the re-establishment of the mangrove ecosystem as well as the habitat formation for the aquatic living (Winterwerp at al., 2020). While their study focuses more on the application of the proposal as an external breakwater, Burrall et al. (2020) look further into a branched foundation system which is found to be 6-10 times more efficient as compared to the conventional micropile system, thus improving the foundation capacity and demonstrates more efficient use of materials and energy.

CONCLUSION

The protection of coastal shorelines and riverine has been the focus of our development strategies, mainly due to their importance to our communities and the ecosystems behind the embankments. While conventional strategies exist, climate change effects, mainly sea level rise, drive the reformation and changes in the approaches taken in proposing solutions in design and the built environment. A regenerative building strategy enables the opportunity to design structures that are able to perform beyond engineering means while providing ecological and social benefits. The study shows that it is possible and practical to abstract the beneficial qualities of mangrove roots as a source of biomimicry inspiration based on the ecological services provided.

Extensive research on the hydrodynamics of the mangroves' roots and roots models have been carried out to further understand the morphological impacts of the roots on the wave attenuation properties. Thus, a systematic literature review would provide better insights into generating a framework of mangrove properties that can be extracted as an embedded architectural approach. This would correlate with the problem-based approach as discussed in the biomimicry approaches.

While a root-like foundation system has been proposed, the conceptual proposal is not simulated for the wave attenuation and sedimentation as would occur in natural systems. Based on the literature review, the potential research gap identified is the integration of wave attenuation properties of mangrove roots into the structural design, which contributes to a regenerative building strategy, benefitting both the built environment and ecosystems. The study could pose importance in biomimicking mangrove features into the structural design in both form and function. Subsequently, the study could provide valuable insights into designing building structures and envelopes that minimise the impact on coastal denudation. Alternatively, due to the limited knowledge, the paper lacks in an in-depth discussion regarding the hydrodynamics processes and the concept of fluid dynamics. Thus, a collaboration with the experts in the field would attribute to a better analysis of both architectural and ecological aspects.

ACKNOWLEDGEMENT

The author would like to acknowledge research funding from Short Term Research Grant, Universiti Sains Malaysia (304/PPBGN/6315590).

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